

## Diurnal Variations in Precipitation and Thunderstorm Frequency over the Conterminous United States<sup>1</sup>

J. M. WALLACE

*Department of Atmospheric Sciences, University of Washington, Seattle 98195*

(Manuscript received 12 November 1974)

### ABSTRACT

Hourly data on the frequencies of all types of precipitation events, heavy precipitation events, trace precipitation events, and thunderstorms for more than 100 stations in the United States were processed to generate statistics on the amplitude and phase of the diurnal and semidiurnal cycles at each station. Results are displayed on seasonal maps in a vectorial format that emphasizes the large scale geographical consistency of the diurnal variations.

During summer each of the four parameters listed above displays a distinctive geographical pattern of diurnal variations. Thunderstorm frequency tends to be the most strongly modulated by the diurnal cycle; trace precipitation the least strongly modulated. Over the central United States the maximum frequency of severe convective storms occurs during the early evening; thunderstorms exhibit their maximum frequency around midnight, while most precipitation falls later in the night. These amplitude and phase differences offer some insight into the relative importance of thermodynamical and dynamical processes in controlling the frequency and intensity of convective activity.

During winter heavy precipitation and thunderstorms are biased toward nighttime over much of the midwest and Atlantic seaboard. Trace precipitation exhibits a small but geographically consistent diurnal oscillation with a peak near or slightly after sunrise. It is suggested that this morning peak is associated with precipitation from low stratus decks.

The semidiurnal cycle is generally smaller than the diurnal. Effects of the  $S_2$  pressure wave are clearly evident over much of the tropics, but over middle latitudes they are often obscured by regional and local influences.

### 1. Introduction

Documentation of the diurnal variability of rainfall has been the topic of well over a hundred published articles, some of which date back to the middle of the 19th century. Hann (1901) attempted to synthesize the results of a large number of earlier investigations in terms of the following interpretation, based upon a simple geographical classification scheme:

- a) In regions with continental climates most precipitation falls in convective showers during the afternoons while over the open oceans and in coastal regions with marine climates maximum rainfall occurs at night or during early morning.
- b) In some regions there are pronounced seasonal differences in the character of the diurnal variability. Over much of western Europe winter precipitation exhibits a nocturnal rainfall maximum while during summer the maximum occurs during the afternoon. Over parts of the monsoon areas of the tropics there is a shift toward morning maxima during the wet season.

The first comprehensive study of the diurnal variability of precipitation over the United States was carried out by Kincer (1916) using summer rainfall data at 175 stations. His results brought to light the existence of two broad regions that did not fit Hann's classification scheme:

- a) At many stations in the central and north central United States more rain falls at night than during the day.
- b) Coastal stations in the southeastern United States show a pronounced afternoon rainfall maximum.

In a subsequent study by Means (1944) it was shown that summer thunderstorms exhibit a diurnal variability similar to that found by Kincer for precipitation. Means' study provided much more detailed information concerning the phase of the diurnal cycle as a function of geographical location. The overall qualitative similarity between Kincer's and Means' results indicates that the diurnal variability of summer precipitation is largely a reflection of the diurnal cycle in convective activity.

To the author's knowledge there have not been any detailed studies of the diurnal variability of wintertime

<sup>1</sup> Contribution No. 329, Department of Atmospheric Sciences, University of Washington.

TABLE 1. Summary of selected publications on diurnal variations in precipitation and thunderstorms. *A* is precipitation amount, *F* is precipitation frequency, and *T* is thunderstorm frequency.

Region	Reference	Parameter	Number of stations	Comments
Africa				
Eastern	Thompson (1957)	<i>A</i>	27	Hourly data by months
Southern	Hastenrath (1970)	<i>F, A</i>	30, 12	By 3-hourly periods for the year
	Union of South Africa Weather Bureau (1954-60)	<i>F, A</i>	10	Hourly data by months
Sudan	Pedgley (1969)	<i>A</i>	17	By 3-hourly periods, monsoon season
	Pedgley (1971)	<i>T</i>	2	By 3-hourly periods, annual
Asia				
India	Prasad (1970)	<i>A</i>	15	Tables of hourly data by months for 8 stations
	Raman and Raghavan (1961)	<i>T</i>	47	Tables of 6-hourly data by seasons for all stations
Japan	Landsberg (1944)	<i>F</i>	22	2-hourly data by months
Middle East	Neumann (1951)	<i>T</i>	5	Daytime vs nighttime frequencies during winter
Malaya	Nieuwolt (1968)	<i>A</i>	11	Hourly data by months
China, Korea	Ramage (1952)	<i>A</i>	>50	Monsoon season, most results presented in qualitative form
Soviet Union	Chirakadze (1959)	<i>A</i>	—	Summer results by 12-hour periods
Central and S. America				
Argentina	Bleeker and André (1951)	<i>T</i>	—	Qualitative, subjective description
Brazil	Ramos (1974)	<i>F</i>	4	Hourly occurrences, Dec-April
El Salvador	Lessmann (1968)	<i>A</i>	7	Hourly data by months
Windward Is.	La Seur (1965)	<i>A</i>	183	Stratification of data by synoptic type
General	Hann and Süring (1939)	<i>A</i>	3	2-hour averages
Europe				
General	Hann (1901)	<i>A, F</i>	12	2-hourly data, some seasonal some annual
	Hann and Süring (1939)			
British Isles	Goldie (1936)	<i>A</i>	>5	Data stratified by synoptic classifications
Sweden	Andersson (1969)	<i>A</i>	42	Monthly data. 12-hour totals expanded in terms of empirical orthogonal functions in the space domain.
Austria	Steinhauser (1965)	<i>A, F</i>	45	2-hourly data by months for all stations
Germany	Röling (1969)	<i>T</i>	8	By 3-hourly periods for year
North America				
United States	Kincer (1916)	<i>A</i>	175	12-hourly rainfall totals for summer. Detailed statistics for selected stations.
	U. S. Weather Bureau (1941)	<i>F, T</i>	58	3-hourly data, by months; Airways Atlas.
	Means (1944)	<i>T</i>	—	Analysis of summer data in Airways Atlas. Hour of peak occurrence.
	U. S. Weather Bureau (1947)	<i>T, F</i>	—	Analysis of 6-hourly data, by seasons. Contains many references.
	Jorgensen (1967)	<i>F</i>	—	Analysis of 6-hourly data, by months
	Rasmusson (1971)	<i>T</i>	294	Summer thunderstorms; amplitude and phase of diurnal and semidiurnal cycles.
	Church (1974)	<i>F</i>	1	References for many studies based on data for individual stations
Open ocean				
	Brooks (1925)	<i>T</i>	1	<i>M.S.S. Challenger</i> cruising in Indian Ocean
	Kraus (1963)	<i>F</i>	9	Weather ships. 3 hourly data, by month, convective vs non-convective precipitation
	Solov'ev (1965)	<i>T</i>	—	Annual data summarized by 3 h period for 11 regions. Appears to be based on relatively small data sample.
Pacific Islands				
	Finkelstein (1964)	<i>A</i>	10	Hourly data by seasons
	Inchauspé (1970)	<i>A, F</i>	4	Hourly data by seasons
	Seelye (1950)	—	—	
	Hull and Pitko (1970)	<i>F</i>	5	Oahu; hourly data by months.

precipitation or thunderstorms over the United States. Six-hourly thunderstorm and precipitation probability statistics published by the U.S. Weather Bureau (1941) and Jorgensen (1967) show little evidence of any pronounced diurnal variability.

The purpose of this study is to provide a comprehensive and consistent documentation of the diurnal variation of thunderstorm activity and precipitation at various intensity levels over the United States during both the summer and winter seasons. By displaying

amplitudes and phases in a vectorial format it is possible to demonstrate the high degree of spatial consistency of the diurnal cycle over broad areas of the country. This display technique also proves to be convenient for comparing the diurnal variability of different parameters. Despite some ambiguities in the interpretation of these amplitude and phase differences, it is possible to glean from them a number of useful insights regarding the nature of the environmental controls upon convective activity. Documentation of these diurnal variations

should also be useful for verification of numerical weather prediction models that include the diurnal cycle, and as ground truth for hourly cloud cover and precipitation statistics derived from the SMS-GOES satellites.

For the reader who is interested in the diurnal variability of precipitation and thunderstorms in a global context, we have provided in Table 1 a partial list of published works that deal with these subjects. From bibliographies in these papers it is possible to gain access to a large number of additional publications.

## 2. Data sources, analysis, and display

This study is based on data from a number of different sources:

1) *Climatology of the United States*, No. 82, "Decennial Census of United States Climate—Summary of Hourly Observations" for the years 1951–60; published by the U.S. Weather Bureau, 1962–1963. Data on the number of precipitation occurrences in the categories: trace, .01, .02–.09, .10–.24-inch per hour: summarized by month and by hour of the day for the 10 yr period. Data for about 120 stations exclusive of Alaska and Hawaii. About 30 of the stations have 5 yr rather than 10 yr of precipitation data.

To supplement these data I requested the National Climatic Center to prepare additional 10 yr summaries for Scottsbluff, Valentine, Grand Island, and North Platte, Neb., Dodge City and Goodland, Kan., and Texarkana, Ark.

2) Statistics on the frequency of the occurrence of thunder at the standard hourly observing times, contained in Part A of the Uniform Summary of Surface Weather Observations, on file at the U.S. Air Force, Environmental Technical Applications Center.

Thunderstorm data from 294 stations with record lengths mostly between 7 and 20 yr are summarized in terms of hourly frequencies for each station. Additional 3-hourly data for Fort Leonard Wood, Mo., and Blytheville, Ark., were provided by the National Climatic Center.

3) Local Climatological Data (LCD) records for the state of Iowa, on file on magnetic tape at the National Climatic Center: a 25 yr record of hourly precipitation data for individual days at about 100 individual stations, archived in a card image format.

4) Tables of frequencies of various cloud types for stations in west Texas, summarized from 3-hourly surface observations by Haragan (1969).

Hourly and 3-hourly data were harmonically analyzed to obtain amplitudes and phases of the diurnal and semidiurnal cycles. Amplitudes were normalized by dividing them by the 24 h mean of the parameter in question. To illustrate the meaning of this statistic, if the normalized amplitude of the diurnal cycle in thunderstorm frequency were equal to 0.33, and if higher

harmonics were absent, then the probability of thunderstorms would be 1.33 times the 24 h mean value at the time of the maximum in the diurnal cycle, and 0.67 times the mean at the time of the minimum; in other words a normalized amplitude of 0.33 implies a 2:1 modulation, neglecting the effects of other harmonics. It should be noted that the normalized amplitude can be greater than 1.0. For example, if thunderstorm frequency were near zero during the night and high during the daytime, with symmetry about a noontime peak, then the normalized amplitude of the diurnal cycle would be greater than 1. In this situation higher harmonics (in particular, a strong semidiurnal cycle centered at noon) would be required to fit the 24 h distribution. Normalized amplitudes between 1.0 and 1.5 are frequently encountered in situations where precipitation events or thunderstorms are strongly suppressed during half the day. This situation is discussed further in reference to the semidiurnal cycle in Section 6.

Results are displayed on maps in a vectorial format where the normalized amplitudes, multiplied by 100, are plotted like wind speeds. In all the figures and in the discussion all times refer to local time unless otherwise indicated. Hourly precipitation data are referred to the midpoint of the hour that they represent (e.g., the 3–4 a.m. precipitation is regarded as occurring at 0330), while the thunderstorm and cloud data are referred to the appropriate observation times which were made on the hour.

In Figs. 1–4 and 7–10, amplitude and phase vectors are plotted only for those stations that recorded at least 200 thunderstorm or precipitation events of the appropriate type during their period of record. For a station with a 10-year record, the "significance criterion" corresponds to an hourly percentage frequency of occurrence of

$$\frac{200 \text{ events}}{3 \text{ mo} \times 30 \text{ d mo}^{-1} \times 24 \text{ h d}^{-1}} \approx 0.9\%$$

for the three-month summer season (June–August) and  $\sim 0.5\%$  for the five-month winter season (November–March). In these figures the observed frequency of occurrence is plotted for each station that approaches the above significance criterion. Since some of the station records are considerably longer than 10 yr for the thunderstorm data and some precipitation records are 5 yr rather than 10, the percentage frequencies quoted above do not always correspond to the lower limits for which amplitude and phase vectors are plotted. At stations denoted by dots without vectors the observed frequency of occurrence is too low to meet the above significance criterion. In combining group stations in Fig. 10, the same criterion was applied; *i.e.*, records from a sufficient number of stations were combined to generate data sets containing at least 200 individual thunderstorm events.



FIG. 1. Normalized amplitude and phase of the diurnal cycle in the total frequency of precipitation, including trace events for the summer season (June-August). Normalized amplitude is indicated by the configuration of barbs on the tails of the arrows, where each half barb represents 5%, each full barb 10%, and each triangular flag 50%. Stations with circles around them have normalized amplitudes less than 2.5%. Phase is indicated by the orientation of the arrows. An arrow pointing from the north indicates a midnight maximum (local time); one pointing from the east indicates a 0600 maximum, etc. The numbers plotted next to the stations represent the 24-hour mean frequencies in terms of percent of hours with precipitation.

In the preparation of Fig. 5, hourly precipitation events were grouped together without regard for station. The numbers of individual events that are the basis for

the data points in the figure range from 200 for the “>1.6 in. h<sup>-1</sup>” category to over 300 000 for the “.01-.03 in. h<sup>-1</sup>” category.

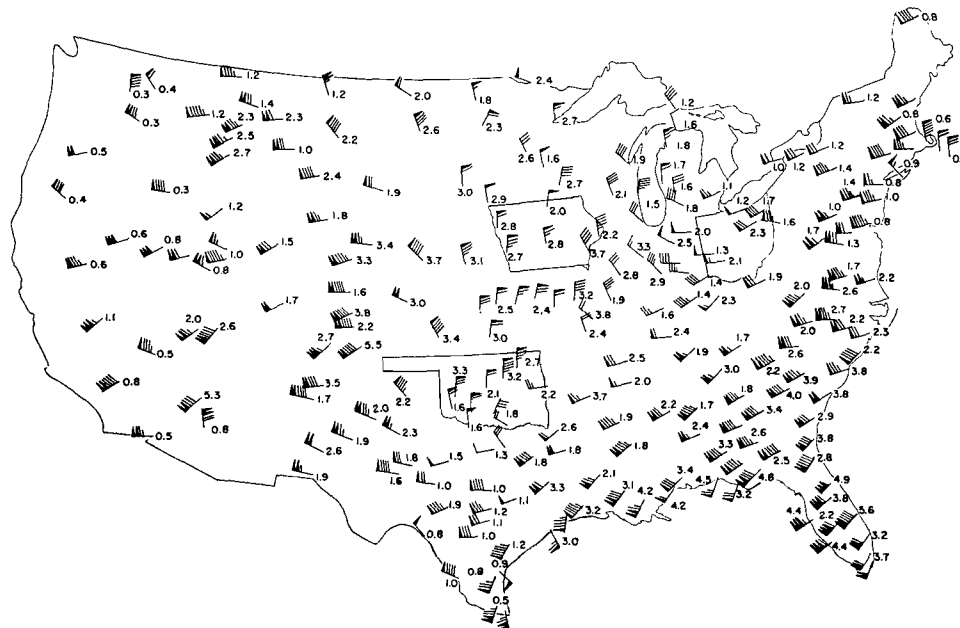


FIG. 2. The diurnal cycle in the thunderstorm frequency during the summer season. Plotting conventions as in Fig. 1.

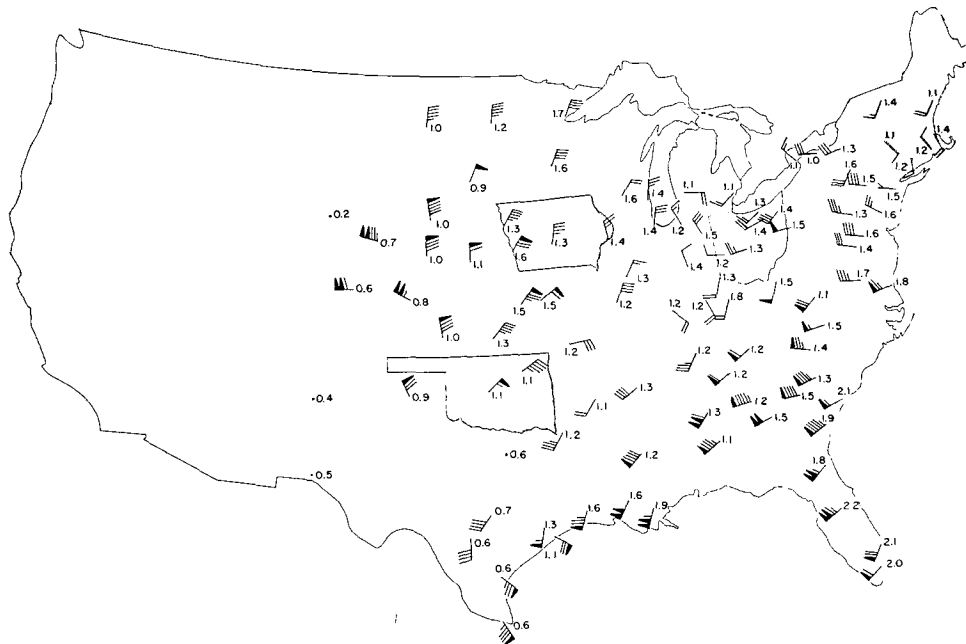


FIG. 3. The diurnal cycle in the frequency of heavy precipitation ( $>0.10$  in.  $h^{-1}$ ) during the summer season. Plotting conventions as in Fig. 1.

### 3. Diurnal variations during the summer season

Figure 1 shows in vectorial form the normalized amplitude and phase of the diurnal cycle in total precipitation frequency during the summer season, June, July, and August. Hours with trace precipitation are counted as contributing to the total number of precipitation events. The numbers plotted next to the stations represent the 24 h mean frequencies in terms of percent of hours with precipitation. The phase and amplitude vectors display a coherent pattern that exhibits the following features:

- Most of the region to the south and east of the Mississippi and Ohio valleys exhibits a strong late afternoon maximum.
- In the lee of the Rockies the greatest chance of precipitation is around 1800 local time. As one moves eastward there is a gradual transition to a nocturnal maximum over the high plains and finally to a 0600 maximum in the low plains.
- Amplitudes are small over the Great Lakes and the Northeast.
- Stations located along the Gulf coast in Texas display late morning maxima.

Figure 2 shows a comparable depiction of the hourly data on thunderstorm frequency. As noted in the previous section, these data are based on reports of audible thunder at the time of the hourly observation, regardless of whether rain was occurring at the time. The 24 h average thunderstorm frequencies plotted in the figure display somewhat more scatter than the

precipitation frequencies in Fig. 1. Some or all of these irregularities may be a consequence of differing periods of record at neighboring stations and differing decibel levels required for thunder to be heard at various stations. Despite the "noise" inherent in the 24 h mean thunder frequencies, the diurnal amplitude and phase vectors show a high degree of spatial consistency, except in mountain areas, where the pattern is strongly influenced by local topography. East of the Rockies, the overall pattern is reminiscent of Fig. 1 but there are some significant differences:

- In most areas thunderstorm frequency exhibits a larger normalized amplitude than precipitation frequency. The difference is particularly notable in the Northeast where there is a strong bias toward afternoon thunderstorms but a nearly equal probability of precipitation at all times of day.
- Over the region of nocturnal thunderstorms in the central part of the country the peak thunderstorm frequency is consistently earlier than the maximum frequency of precipitation. The difference is on the order of six hours over much of the Mississippi valley and even larger in the parts of Illinois, Indiana, and Ohio that lie in the transition zone between the nocturnal and afternoon maxima.

The results shown in Fig. 2 have already been presented in scalar form by Rasmusson (1971). The distribution of amplitudes and phases closely replicates the one that Means (1944) derived subjectively from a largely different data base.

Figures 3 and 4 are depictions of the diurnal cycles in the frequencies of "heavy" precipitation ( $\geq 0.10$  inch  $h^{-1}$ ) and trace precipitation, respectively. "Heavy" precipitation events are for the most part identifiable with convective activity, especially during summer. Interpretation of trace events in hourly data is more ambiguous, because such events may be associated with widely differing types of precipitation; e.g., prolonged periods of light drizzle, snow flurries, sprinkles from weak showers, or from more vigorous storms that don't pass directly over the station, etc. Despite these ambiguities the diurnal variation of the frequency of trace events is of considerable interest by virtue of the fact that of the various parameters readily available, it is the most sensitive to variations in light precipitation from stratiform clouds. From an intercomparison of the four figures we note the following:

- g) Heavy precipitation displays largely the same diurnal variation as thunderstorm frequency, presumably because both parameters are indicators of the intensity of convective activity.
- h) From a careful comparison of Figs. 2 and 3 it is evident that thunderstorm frequency exhibits somewhat larger amplitudes than the frequency of heavy precipitation. The differences are not as large as noted in (e) above, but they are still significant, particularly over the Northeast.
- i) In the region of nocturnal thunderstorms the peak thunderstorm frequency occurs earlier in the night than the peak frequency of heavy precipitation. The differences in phases is roughly half as large as noted in (f). Further evidence concerning these phase differences is presented in (1) below.
- j) Of the various precipitation categories, traces tend to be the least strongly modulated by the diurnal cycle. (A notable exception is the regions of California that are susceptible to incursions of marine air during the hours around sunrise.)
- k) Throughout much of a triangular shaped area extending from Oklahoma to Michigan to North Dakota there is a tendency for an out of phase relationship between thunderstorm activity and trace precipitation events; the former having a maximum near midnight and the latter peaking between sunrise and noon. This is the behavior that would be expected if the diurnal variability of trace precipitation in this region were dominated by a modulation of light precipitation from low, stratiform cloudiness with a maximum during the morning hours. Further evidence in support of this hypothesis will be presented in (n) and (q) below.

In order to provide a more comprehensive description of the phase differences, pointed out in (f) and (i) above, between the diurnal cycles in the frequencies of total precipitation, heavy precipitation, and thunderstorms in the central part of the country, an analysis of the hourly precipitation data on the LCD tapes for the state of Iowa was performed. Results are presented in Fig. 5, which shows on a harmonic dial amplitudes and phases of the diurnal cycles in the hourly precipitation data, stratified according to intensity levels as indicated in the legend. Also included in the figure are results for total rainfall amount at Iowa stations (based on the LCD tapes), trace precipitation for Des Moines only (trace data are no longer available on the LCD tapes)

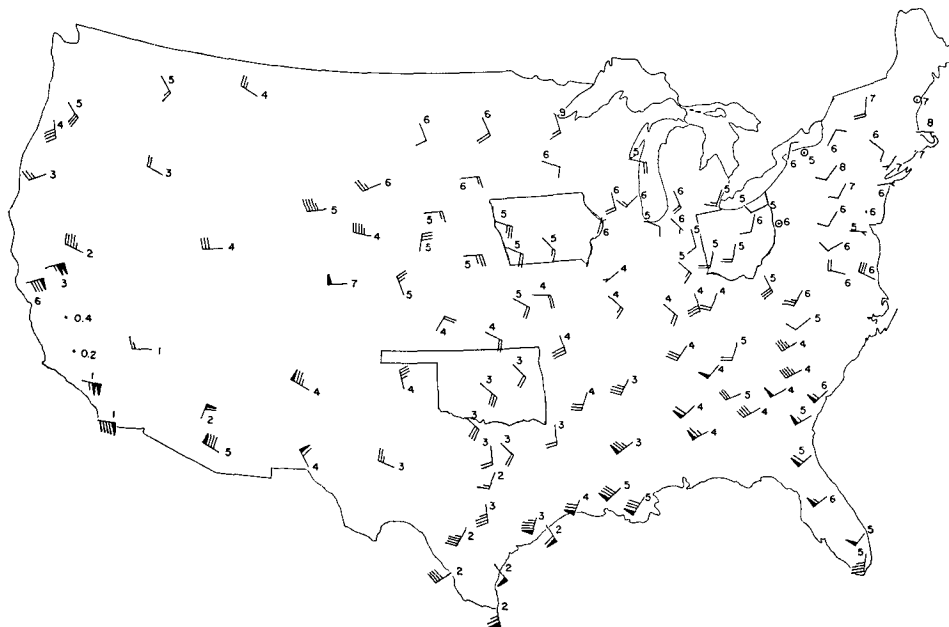


FIG. 4. The diurnal cycle in the frequency of trace precipitation during the summer season. Plotting conventions as in Fig. 1.

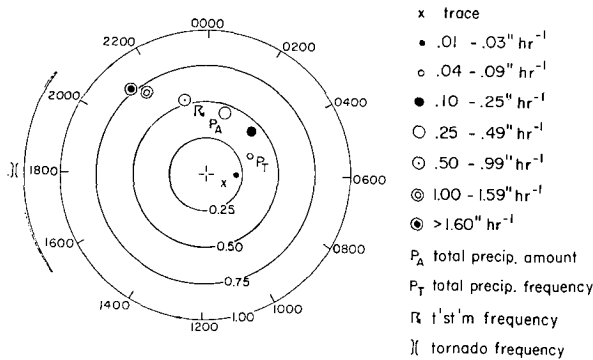


FIG. 5. Harmonic dial representation of normalized amplitude and phase of the diurnal cycle in the frequency of precipitation events in various intensity categories for Iowa stations during the summer season. Consult text for further details.

so it was necessary to revert to the decennial census), and tornado frequency for Iowa, Nebraska, Minnesota, and the Dakotas, based upon data given in Fig. 6 of House (1963) and consistent with results of Spohn and Waite (1962). The points in the figure lie within a spiral band that progresses outward toward larger normalized amplitudes and backward in time with increasing intensity level. These results suggest the following conclusions:

- 1) In the region of nocturnal thunderstorm maxima, severe storms that produce tornadoes and flooding are most likely to occur between 1600 and 2200. Thunderstorm activity of all types is most frequent around midnight while rain, with or without thunder, is most probable in the hours after midnight. Note that the diurnal oscillation in total precipitation frequency has a maximum around 0400. Light precipitation has its highest frequency of occurrence still later, around sunrise. In general, the higher the intensity of the precipitation, the stronger the modulation by the diurnal cycle.

Three-hourly data on frequencies of various cloud types in west Texas compiled by Haragan (1969) provide an opportunity to extend the analysis in Fig. 5 a little further. Depicted in Fig. 6 are the diurnal cycles in various cloud and precipitation parameters for the summer season at Amarillo, again in the form of a harmonic dial. From an inspection of the figure it is possible to follow the course of weather events on an idealized "typical" summer day in the southern part of the high plains:

- m) Consistent with Figs. 1-4 the maximum probabilities of occurrence of thunderstorms, "heavy," total, and trace precipitation all occur around 2200 together with the maximum frequency of cumulonimbus cloud types.
- n) The frequency of stratus cloud types exhibits a strong diurnal cycle with a maximum just after

sunrise. This maximum might be accompanied by a peak in light, stratiform precipitation, as discussed in (k) above. If such a peak were present it might not necessarily be reflected in trace precipitation statistics which, over the high plains, are strongly dominated by the diurnal cycle in convective activity.

- o) Altocumulus cloud types show a distinct peak near 0600. A morning maximum has been observed at Arizona stations during summer (Sellers, 1958).

The diversity of behavior of various cloud types argues against use of hourly averages of total cloudiness in the "Decennial Census" to document the diurnal variation in total cloud amount over the United States. In order to provide results that can be interpreted in terms of physical processes it is clear that such a documentation would have to treat the various cloud types on an individual basis. To the author's knowledge, the data base required for such an undertaking is not available in a summarized form.

Diagrams similar to Fig. 6 have been prepared for the neighboring stations Midland and Lubbock, for which Haragan also provided cloud statistics. The results are so similar to those already shown that they will be omitted for the sake of brevity.

#### 4. Diurnal variations during the winter season

Figure 7 shows the amplitude and phase of the diurnal cycle in total precipitation for the winter season,

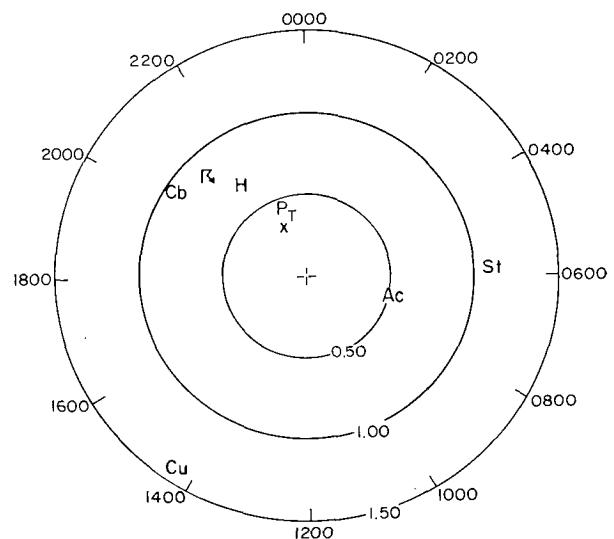


FIG. 6. Harmonic dial representation of normalized amplitude and phase of the diurnal cycle in the frequency of thunderstorms, precipitation and various cloud types at Amarillo during the summer season. Cloud types are denoted by their usual abbreviations. H denotes precipitation events >0.10 in. h<sup>-1</sup>. Other symbols have the same meaning as in Fig. 5. Consult text for further details.

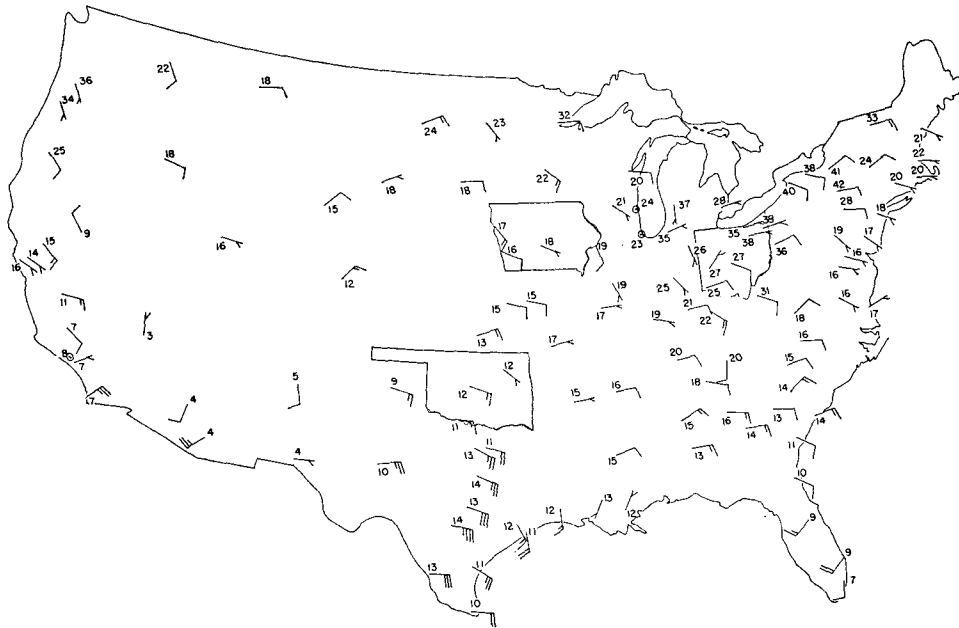


FIG. 7. The diurnal cycle in the total frequency of precipitation, including trace events, during the winter season November–March. Plotting conventions as in Fig. 1.

December–March. Amplitudes are much smaller than those for the summer season but the phases still display a coherent large scale pattern with the following properties:

- p) Over most of the central and eastern United States there is a very weak diurnal modulation of total precipitation frequency with a maximum around sunrise. Notable exceptions are the Florida

peninsula, where there is a strong bias toward afternoon precipitation, probably of a convective nature, and Texas and Oklahoma where the morning peak is considerably stronger than in other regions. There are not enough observations to resolve the pattern in the western part of the country, but morning maxima seem to be prevalent at most stations.



FIG. 8. The diurnal cycle in the frequency of heavy precipitation ( $>0.10 \text{ in. h}^{-1}$ ) during the winter season. Plotting conventions as in Fig. 1.

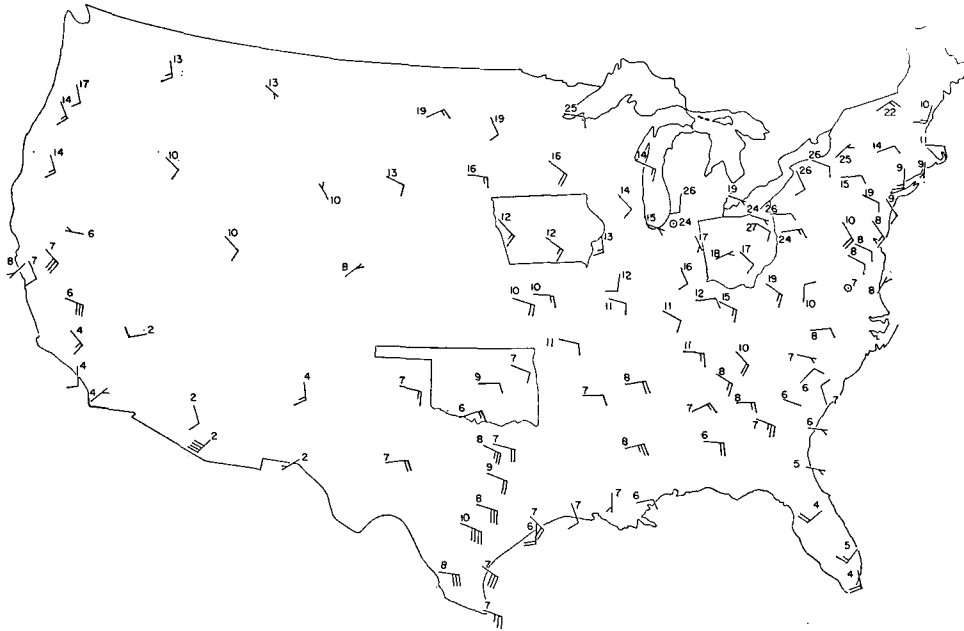


FIG. 9. The diurnal cycle in the frequency of trace precipitation during the winter season. Plotting conventions as in Fig. 1.

A much stronger diurnal dependence emerges when the precipitation data are stratified according to intensity level. Figures 8 and 9 show the diurnal variations in "heavy" and trace precipitation, respectively. From a comparison of Figs. 7, 8, and 9, the following relationships are apparent:

- q) Contrary to the summer results, trace precipitation exhibits a stronger diurnal modulation than

total precipitation in most areas. With the exception of the Florida peninsula and a few other isolated areas in mountain and coastal regions, the maximum occurs during the first few hours after sunrise. This morning maximum may be associated with drizzle and light snow showers from low, stratiform cloudiness as hypothesized in (k) above. The reduction in convective activity and increase

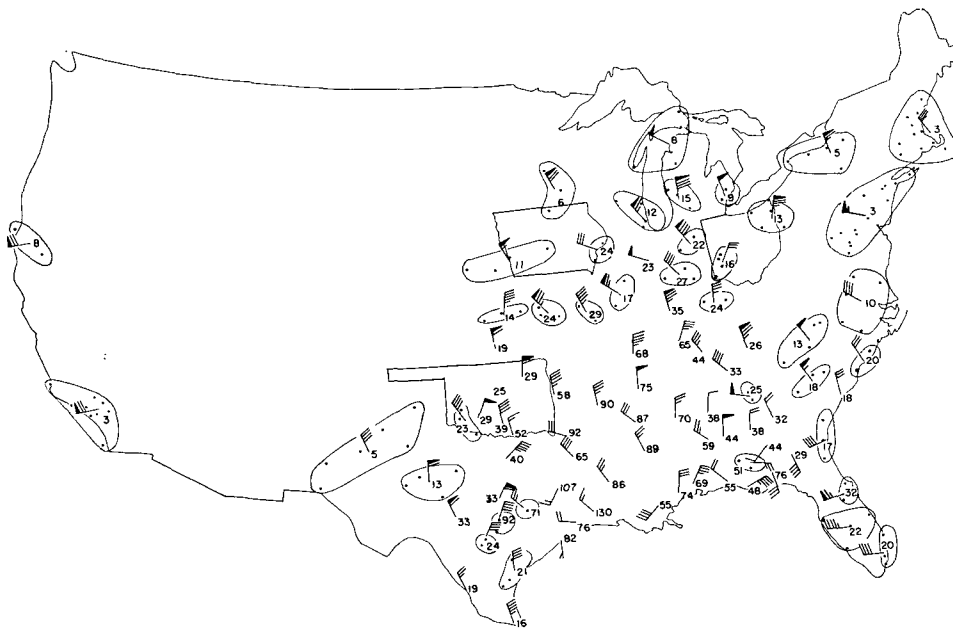


FIG. 10. The diurnal cycle in thunderstorm frequency during the winter season. Plotting conventions as in Fig. 1 except that 24-hour mean percentage frequencies are expressed in hundredths of a percent. Dots represent stations that were grouped together in the calculations.

in frequency of stratiform precipitation from summer to winter would explain why the morning maximum emerges more clearly and is more widespread in the winter trace data. The above interpretation is consistent with synoptic experience in Texas where the morning maximum is particularly pronounced.<sup>2</sup>

- r) "Heavy" precipitation events exhibit a pronounced diurnal cycle with a nocturnal maximum over much of the northern and eastern part of the country. Maxima occur between 0400 and 0800 along most of the eastern seaboard and close to midnight in much of the Midwest. Amplitudes are small in comparison to summer but over much of the Northeast and the Midwest they are large enough to account for about a 2:1 ratio in the frequency of heavy precipitation events between the times of maximum and minimum.

Most heavy precipitation events during winter are associated with convective cells imbedded within frontal cloud bands of cyclonic storms. A few of these cells are vigorous enough to produce thunder. Thus it is to be expected that the frequency of winter thunderstorms should display a diurnal variation similar to that of heavy precipitation.

Because of the relatively low frequency of winter thunderstorms it was necessary to combine the data for groups of neighboring stations in order to obtain a statistically reliable determination of amplitude and phase. The results, shown in Fig. 10, still display considerable scatter because of the inhomogeneity of the station records and the smallness of the sample. Nevertheless, the following conclusions appear to be warranted:

- s) With the exception of Florida, southern Georgia, and parts of the Gulf coast, nocturnal maxima are prevalent. Amplitudes are generally larger than those in the heavy precipitation data.
- t) Within the general area of the nocturnal maxima there is some evidence of large-scale patterns. For example, as one passes from west to east across Illinois, Indiana, and Ohio, the time of the peak thunderstorm activity shifts from before to after midnight. In an inspection of historical weather maps it is possible to find a number of cases in which individual squall lines displayed the same timing as these climatological statistics. However, there is so much variability among individual thunderstorm outbreaks that I hesitate to propose any synoptic interpretation of the phase shift. There is also a large amplitude change and phase shift between Texas and Louisiana that appears in both the thunderstorm and heavy precipitation data.

<sup>2</sup> R. A. Houze, University of Washington, personal communication.

From a practical standpoint the most significant finding that emerges from the analysis of the wintertime data is the documentation of a substantial diurnal cycle in convective activity with highest frequency during the night. Existence of this phenomenon has been hinted at in a number of previous publications (Davis, 1892; Humphreys, 1927) but to the author's knowledge it has never been documented in data over the United States. As pointed out in the introduction, the existence of a nocturnal maximum in wintertime precipitation over western Europe has been known at least as far back as the work of Hänn (1901), and it is mentioned in a number of the studies listed in Table 1.

## 5. Physical interpretation

On the basis of results presented in Sections 3 and 4, it is hypothesized that the diurnal cycle in precipitation results from the combination of a modulation in convective activity and a modulation in light precipitation from shallow, stratiform cloudiness, both of which occur in response to the diurnal cycle in solar heating.

### a. Convective activity

The diurnal cycle in convective activity is strong throughout the year, but its influence is most noticeable during summer when the overall frequency of convection is highest. The timing of maximum convection displays a high degree of geographical variability during summer, whereas during winter nocturnal maxima seem to be prevalent in temperate latitudes of the central and eastern United States. In some parts of the country, severe thunderstorms and more ordinary showers and thunderstorms display substantial differences in timing with respect to the maximum frequency of occurrence.

The large number of mechanisms that have been proposed, over the years, to explain the diurnal cycle in convective activity can be grouped into two categories: those based on thermodynamical processes that affect the static stability, and those based on dynamical processes that influence the mass convergence within the planetary boundary layer.

Over land the diurnal cycle in sensible heat flux from the ground produces a large modulation in the static stability of the lower troposphere, creating conditions most favorable for convective activity during afternoon. A variety of competing thermodynamical mechanisms have been proposed to explain the nocturnal thunderstorm maximum over the central United States during summer; e.g., radiative cooling from cloud tops (Hewson, 1937) and low-level warm advection (Means, 1944). Although it is plausible that these processes act to destabilize the atmosphere at night, their effectiveness in counteracting the very large diurnal cycle in sensible heat flux from the ground has never been demonstrated.

Over much of the United States during summer, the vertical stratification is convectively unstable 24 h a



FIG. 11. 00–12 GMT mean wind difference vectors at the reporting level nearest 500 m above each station during the summer season.

day. Bleeker and André (1951) were the first to point out that under such conditions even a small diurnal cycle in low-level convergence and lifting at the top of the planetary boundary layer may be sufficient to control the timing of convection. There are at least three physical processes that are capable of producing diurnal variations in boundary layer convergence:

- i) the familiar land and seabreeze circulation in coastal areas;
- ii) a uniform diurnal heating cycle in regions of sloping terrain (Holton, 1966; Lettau, 1967); and
- iii) changes in frictional drag associated with the diurnal variation in static stability within the planetary boundary layer (Blackadar, 1957).

It seems quite likely that the late morning maximum in summer precipitation and thunderstorms along parts of the Texas coast and the nighttime maximum on Cape Cod, Nantucket, and Long Island are associated with the first mechanism.

It has been demonstrated quite convincingly by Hering and Borden (1962) and Pitchford and London (1962) that the nocturnal maximum in convective activity over the central United States during summer is related to the occurrence of the so called "low-level jet," a nighttime phenomenon that results from a large-scale diurnal oscillation in the boundary layer circulation centered over the southern Great Plains. The clima-

tology of low-level jet occurrences has been documented by Bonner (1968). The strong geographical dependence and the preferred orientation of the jet is evidence that the second mechanism cited above plays an important role in the boundary layer dynamics of this region. The strong bias of jet occurrences toward days with mean southerly or southwesterly low-level flow is evidence of the importance of the third mechanism. When the mean wind blows from these directions the boundary layer oscillations associated with (ii) and (iii) reinforce each other and produce strong winds during the night when the oscillatory wind component lines up with the mean wind. The nocturnal maximum in convective activity over the central United States during summer appears to be a consequence of the combined effects of (ii) and (iii), under conditions of southerly or southwesterly flow which is common over the southern Great Plains during summer.

It is possible to obtain a qualitative impression of the diurnally oscillating pattern of boundary layer convergence over the southern United States during summer from Fig. 11, which shows the mean difference field between the 0000 and 1200 GMT wind vectors at reporting levels near 500 m above the ground. Data shown in the figure have been taken from a number of different sources: Wallace and Hartranft (1969), Fig. 2.6 of Wees (1970) and statistics compiled from a sampling of 52 summer days, selected at random from

the Northern Hemisphere Data Tabulations. Over the southern United States the mean wind difference vectors are so large that they should be well represented, even in this inhomogeneous and rather small data sample. In a qualitative sense at least, these wind difference vectors (when divided by 2) are representative of the diurnally oscillating component of the wind field at 0000 GMT (1800 CST and 1900 EST).

From Fig. 11 it is readily seen that on a typical summer day around 1800, near or just after the time when the stratification has reached its most unstable values, the boundary layer wind field is strongly convergent over the regions of the southeastern United States and along the east slopes of the Rockies where there are strong late afternoon peaks in convective activity. Meanwhile there is strong boundary layer divergence in the Plains states from Oklahoma northward, where late afternoon convective activity tends to be suppressed.

The strong correspondence between the timing of the maximum in low-level convergence and the maximum convective activity suggests that the diurnal oscillation in convective precipitation is controlled almost completely by dynamical processes. On the other hand, the severity of the convection seems to be strongly influenced by thermodynamical processes. Over much of the central United States the occurrence of severe storms is strongly biased toward 1800 when the level of convective instability is near its highest value. Severe storms occur only on those days on which the boundary layer convergence associated with the passage of synoptic disturbances is large enough to counteract the "climatological" divergence and subsidence associated with the diurnal oscillation in the planetary boundary layer circulation. The proclivity of the central United States toward the occurrence of severe storms may be due, in part, to the effects of this climatological afternoon subsidence in suppressing more modest forms of convective activity that ordinarily prevent the buildup of extremely unstable stratification in the lower troposphere.

The prevalence of a nocturnal maximum in wintertime convective activity over much of the central and eastern United States requires a somewhat different explanation, but it is possible that it may also be interpreted in terms of dynamical processes. Most wintertime convection is associated with the passage of developing cyclonic storms. In the warm sector of these disturbances nighttime inversions are common, and therefore, in a statistical sense at least, winds near the top of the planetary boundary layer should be stronger during the late night hours, in line with (iii) above. Increased wind speeds within the warm sector should contribute to the overall amount of lifting above the warm frontal surface where wintertime convection often occurs. In this respect it is interesting to note that Goldie (1936) found evidence of a nocturnal maximum in warm frontal precipitation over Scotland during

winter at a time when cold frontal precipitation exhibited a maximum frequency of occurrence during the afternoon. Further evidence of the enhancement of warm frontal precipitation during the nighttime hours was given by Dexter (1944). A crucial test of this hypothesis will come when satellite derived statistics on the diurnal cycle in convective activity over middle latitude oceans become available. If the above hypothesis is correct, then we should expect to find little or no diurnal oscillation in wintertime convective activity over the sea. (An analysis of weather ship data by Kraus (1963) showed little evidence of any diurnal variation in precipitation frequency during winter. However, in Kraus' study the heavy precipitation events and thunderstorms were not dealt with separately as they were in Section 4 above and therefore, in the author's opinion, the possibility of the existence of a diurnal oscillation in wintertime convection over the sea cannot be completely ruled out at this time.)

#### *b. Precipitation from stratiform cloud decks*

Statistics on the occurrence of light precipitation reflect the possible existence of a weak but geographically rather uniform oscillation in light precipitation from low cloud decks, with maximum frequency of occurrence within the first few hours after sunrise. In view of the geographical uniformity of the phase of the oscillation it is plausible that in some areas it might be interpreted purely in terms of local processes such as radiative and turbulent fluxes, as in the model of Kraus (1963). However, in areas such as Texas and along the California coast, where the oscillation appears to be particularly strong, it is likely that mesoscale and/or large scale boundary layer circulations are also important.

### 6. The semidiurnal cycle

Over large areas of the tropical and subtropical oceans the semidiurnal oscillation in precipitation and thunderstorms is as large or larger than the diurnal cycle (see, for example, Inchauspé, 1970). Brier and Simpson (1969) demonstrated quite convincingly that at least in the tropics the second harmonic of the diurnal cycle in cloudiness and precipitation is intimately related to the  $S_2$  pressure wave that is forced by the heating of ozone in the upper stratosphere.

In some published works on the diurnal march of thunderstorms and various precipitation parameters at middle latitude land stations, there is mention of secondary maxima and minima, thus indicating the existence of a pronounced semidiurnal cycle at these latitudes as well. For example, Church (1974) has recently shown evidence of a dominant semidiurnal cycle in light precipitation in Seattle. In the present study there also appeared a number of cases in which the amplitude of the second harmonic of the diurnal



FIG. 12. Normalized amplitude and phase of the semidiurnal cycle in the total frequency of precipitation, including trace events, during the winter season. Normalized amplitudes are plotted using the same conventions as described in the caption of Fig. 1. Phase is indicated by the orientation of the arrows. An arrow pointing from the north is indicative of 0000 and 1200 maxima (local time), one pointing from the east is indicative of 0300 and 1500 maxima, etc.

cycle was larger than that of the first harmonic. However, these cases were generally observed in localized regions in which the diurnal cycle is small (e.g., during summer near Dallas and Ft. Worth). It was found that over most of the country the first harmonic of the diurnal cycle is strongly dominant. For summer thunderstorm frequency over the United States, Rasmusson (1971) has shown that with the exception of a few small areas, the amplitude of the first harmonic is at least twice as large as that of the second. Results of the various studies cited in Table 1 suggest that the same is true in other regions of middle latitudes.

The interpretation of the semidiurnal cycle is ambiguous in regions where the normalized amplitude of the diurnal cycle is of order unity. In such regions the constraint that precipitation or thunderstorm frequency cannot be negative inevitably leads to the introduction of higher harmonics of the diurnal cycle, even if the forcing is purely sinusoidal with a diurnal period. For example, the inherent nonlinearity in the response to a strong diurnal cycle in low-level convergence with a maximum at 1600 would give rise to a semidiurnal oscillation in convective activity with maxima at 0400 and 1600.

In recognition of this ambiguity we have displayed results for the semidiurnal cycle only for total precipitation frequency during the winter season, in which the diurnal cycle is quite small over most of the country. Results displayed in Fig. 12 show some evidence of coherent patterns despite the smallness of the amplitudes. Over most of the southern part of the country

the maximum probability of precipitation occurs around 7 A.M. and 7 P.M., the times of maximum convergence associated with the  $S_2$  pressure wave (see Brier and Simpson, 1969). However, over some parts of the country, such as the North Central states, the phases deviate considerably from these times. Thus in middle latitudes it appears that the  $S_2$  tide is often obscured by more local effects that modulate the daily precipitation cycle.

*Acknowledgments.* The author is grateful to Prof. Phil E. Church whose results concerning diurnal variations in Seattle precipitation originally stimulated his interest in this subject, to Mark Albright and Ernest Recker who performed most of the computations and participated in the analysis of the results, to Dr. Eugene Rasmusson who kindly provided the thunderstorm data, and to Prof. Robert Houze who provided a number of insights regarding the interpretation of the results. The work was supported by the National Science Foundation under Grant No. GA-32439. The manuscript was written while the author was on leave to the Advanced Study Program at the National Center for Atmospheric Research.

#### REFERENCES

- Andersson, T., 1969: The diurnal variation of precipitation in Sweden. *Geografiska Annaler, Ser. A*, **51**, 176-184.  
 Blackadar, A. K., 1957: Boundary layer wind maxima and their significance for the growth of nocturnal inversions. *Bull. Amer. Meteor. Soc.*, **38**, 283-290.  
 Bleeker, W., and J. Andre, 1951: On the diurnal variation of

- precipitation, particularly over central U. S. A., and its relation to large-scale orographic circulation systems. *Quart. J. Roy. Meteor. Soc.*, **77**, 260-271.
- Bonner, W. D., 1968: Climatology of the low level jet. *Mon. Wea. Rev.*, **96**, 833-849.
- Brier, G. W., and J. Simpson, 1969: Tropical cloudiness and rainfall related to pressure and tidal variations. *Quart. J. Roy. Meteor. Soc.*, **95**, 120-147.
- Brooks, C. E. P., 1925: The distribution of thunderstorms over the globe. *Geophys. Mem.*, No. 24. Gr. Brit. Meteor. Off., pp. 147-164.
- Chirakadze, G. I., 1959: Diurnal precipitation distribution over the Georgian S. S. R. *Issledovaniia Gidrometeorologicheskii Institut*, Trudy, No. 5, 124-130.
- Church, P. E., 1974: Some precipitation characteristics of Seattle. Submitted to *Weatherwise*.
- Davis, W. M., 1892: Note of winter thunderstorms. *American Meteorological Journal*, **9**, 164-170.
- Dexter, R. V., 1944: The diurnal variation of warm frontal precipitation and thunderstorms. *Quart. J. Roy. Meteor. Soc.*, **70**, 129-137.
- Finkelstein, J., 1964: Diurnal variation of rainfall amount on tropical Pacific islands. *Proc., Symposium on Trop. Meteor., Rotorua, N.Z., Nov. 1963*, New Zealand Meteor. Serv., Wellington, 286-294.
- Goldie, A. H. R., 1936: Rainfall at fronts of depressions. *Geophys. Mem.*, No. 69, Gr. Brit. Meteor. Off., 18 pp.
- Hann, J., 1901: *Lehrbuch der Meteorologie*, 1st ed., Leipzig, Chr. Herm. Tauchnitz, 338-346.
- , and R. Süring, 1939: *Lehrbuch der Meteorologie*, 5th ed., Leipzig, Willibald Keller, Vol. 1, 448-454.
- Haragan, D. R., 1967: A cloud census investigation for the Texas high plains. Rep't. No. 17, Atmospheric Science Group, Univ. of Texas College of Engineering, Austin, 70 pp.
- Hastenrath, S., 1970: Diurnal variation of rainfall over Southern Africa. *Notos*, **19**, 85-94.
- Hering, W. S., and T. R. Borden, Jr., 1962: Diurnal variations in the summer wind field over the central United States. *J. Atmos. Sci.*, **19**, 81-86.
- Hewson, E. W., 1943: The application of wet-bulb potential temperature to air mass analysis. *Quart. J. Roy. Meteor. Soc.*, **63**, 323-335.
- Holton, J. R., 1968: The diurnal boundary layer wind oscillation above sloping terrain. *Tellus*, **19**, 199-205.
- House, D. C., 1963: Forecasting tornadoes and severe storms. *Meteor. Monogr.*, **5**, No. 27, 141-146.
- Hull, A. N., and J. Pitko, 1972: Climatology of rainfall probability of Oahu, Hawaii. N.O.A.A., N.W.S. Tech. Memo. PR-10, 48 pp.
- Humphreys, W. J., 1927: The greater increase in size and intensity of the extratropical cyclone by night than by day. *Mon. Wea. Rev.*, **55**, pp. 496.
- Inchauspé, J., 1970: Diurnal precipitation variations over atolls of French Polynesia. *La Meteorologie*, Ser. 5, No. 16, 83-95.
- Jorgensen, D. L., 1967: Climatological probabilities of precipitation for conterminous United States. ESSA Tech. Rep. WB-5, Silver Spring, Md., 60 pp.
- Kincer, J. B., 1916: Daytime and nighttime precipitation and their economic significance. *Mon. Wea. Rev.*, **44**, 628-633.
- Kraus, E. B., 1963: The diurnal precipitation change over the sea. *J. Atmos. Sci.*, **20**, 551-556.
- Landsberg, H. E., 1944: A climatic study of cloudiness over Japan. Dept. of Meteor., Univ. of Chicago Misc. Rep. No. 15, 96 pp.
- La Seur, N. E., 1965: Some climatic and synoptic influences on diurnal variations of rainfall on the Windward Islands. *Proc. 4th Army Conf. on Tropical Meteor.*, May 6-7, 1965, p. 96-106.
- Lessman, H., 1968: Types of precipitation in El Salvador Central America. *Wetter und Leben*, **20**, 47-61.
- Lettau, H., 1967: Small to large scale features of the boundary layer structure over mountain slopes. *Proc. Symposium on Mountain Meteorology*, Dept. of Atmos. Sci., Colorado State University, 221 pp.
- Means, L. L., 1944: The nocturnal maximum occurrence of thunderstorms in the midwestern states. Dept. of Meteor., Univ. of Chicago Misc. Rep. No. 16, 37 pp.
- Neumann, J., 1951: Land breezes and nocturnal thunderstorms. *J. Meteor.*, **8**, 60-67.
- Nieuwolt, S., 1968: Diurnal rainfall variation in Malaya. *Assoc. of Amer. Geographers Annals*, **58**, 313-326.
- Pedgley, D. E., 1969: Diurnal variation of the incidence of monsoon rainfall over the Sudan. *Meteor. Mag.*, **98**, 97-106, 129-134.
- , 1971: Diurnal incidence of rain and thunder at Asmara and Addis Ababa, Ethiopia. *Meteor. Mag.*, **100**, 66-71.
- Pitchford, K. L., and J. London, 1962: The low level jet as related to nocturnal thunderstorms over Midwest United States. *J. Appl. Meteor.*, **1**, 43-47.
- Prasad, B., 1970: Diurnal variation of rainfall in India. *Indian J. Meteor. Geophys.*, **21**, 443-450.
- Ramage, C. S., 1952: Diurnal variation of summer rainfall over east China, Korea, and Japan. *J. Meteor.*, **9**, 83-86.
- Raman, P. K., and K. Raghavan, 1961: Diurnal variation of thunderstorms in India during different seasons. *Indian J. Meteor. and Geophys.*, **12**, 115-130.
- Ramos, R. P. L., 1974: Precipitation characteristics in the northeast Brazil dry region. Paper No. 224, Dept. Atmosph. Sci., Colorado State University, Ft. Collins, 56 pp.
- Rasmusson, E. M., 1971: Diurnal variation of summertime thunderstorm activity over the U. S. Tech. Note 71-4, U.S. Air Force Environmental Technical Applications Ctr., Bldg. 159, Navy Yard Annex, Washington, D.C. 20333, 12 pp.
- Röling, H., 1969: Changes in atmospheric pressure due to thunderstorms. *Meteorologische Abhandlungen*, **91**, No. 4, 47 pp.
- Seelye, C. J., 1950: Rainfall and its variability over the central and southwest Pacific. *N. Z. J. Sci., Tech. Sec. B.*, **32**, 11-24.
- Sellers, W. D., 1958: The annual and diurnal variation of cloud amounts and cloud types at six Arizona cities. Sci. Rept. No. 8, University of Arizona, Inst. of Atmos. Phys., 104 pp.
- Solov'ev, V. A., 1965: Diurnal and annual variation of thunderstorm activity in the N. Atlantic Ocean and the seas of western Europe and the Far East. *Meteorologiya, Gidrologiya*, **10**, 32-36.
- Spohn, H. R., and P. J. Waite, 1962: Iowa Tornadoes. *Mon. Wea. Rev.*, **90**, 398-406.
- Steinhauser, F., 1965: Diurnal variations of precipitation in the eastern Alps. *Geofis. Meteor.*, **14**, 115-124.
- Thompson, B. W., 1957: The diurnal variation of precipitation in British East Africa. E. Afr. High Commission Meteor. Dept., Tech. Mem. No. 8, 70 pp.
- Union of South Africa Weather Bureau, 1954-60: *Climate of South Africa*, Part II, Rainfall Statistics, Dept. of Commerce, Pretoria, 187 pp.
- U. S. Weather Bureau, 1941: Airways Meteorological Atlas for the United States. W. B. No. 1314, 163 pp.
- , 1947: *Thunderstorm Rainfall*. Hydrometeor. Rept. No. 5. (In cooperation with Engineering Dept., Corps of Engineers, Washington, D.C.), in two volumes, 671 pp.
- Wallace, J. M., and F. R. Hartranft, 1969: Diurnal wind variations, surface to 30 km. *Mon. Wea. Rev.*, **97**, 446-455.
- Wees, E. L., 1969: Low level diurnal wind variations of the Great Plains. M.S. Thesis, Dept. of Atmos. Sci., University of Washington, Seattle, 77 pp.